

# Spectra and time variability of Galactic black-hole X-ray sources in the low/hard state

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**Abstract.** We propose a jet model for the low/hard state of galactic black-hole X-ray sources which explains a) the X-ray spectra, b) the time-lag spectra, and c) the increase of the amplitude of variability (quasiperiodic oscillations and high frequency) with increasing photon number. The model (in its simplest form) assumes that i) there is a uniform magnetic field along the axis of the jet, ii) the electron density in the jet is inversely proportional to the distance from the black hole, and iii) the jet is hotter near its center than at its periphery. We have performed Monte Carlo simulations of Compton upscattering of soft photons from the accretion disk and have found power-law high-energy spectra with photon index in the range 1.5 - 2, power-law time lags versus Fourier frequency with index 0.7, and an increase of the rms amplitude of variability with photon energy as it has been observed.

## INTRODUCTION

The continuum X-ray spectra of black-hole candidates are generally described by a soft component, normally modeled as a multi-colour black-body component (Mitsuda et al. [22], but see Merloni et al. [20]) and a power-law hard tail, which is thought to be the result of Comptonization (see e.g. Sunyaev & Titarchuk [30]; Hua & Titarchuk [12]; Titarchuk et al. [33]; Psaltis [26]). Based upon the presence or absence of the soft component, the luminosity and spectral slope of the hard tail and the different shapes of the noise components in the power-density spectra, black-hole systems can be found in at least two spectral states: The low/hard and the high/soft states. In the low/hard state the soft component is weak or absent, whereas the hard tail extends to a few hundred keV in the form of a power law with photon-number index in the range 1.5 - 2. The power spectrum shows strong band-limited noise with a typical strength of 20% - 50% rms and a break frequency below 1 Hz [34].

There is growing evidence that all X-ray binaries harboring a black hole display radio emission when they are in the low/hard X-ray state [9]. Inverse Compton scattering by relativistic electrons in a jet has been proposed as a mechanism for the production of X-rays and  $\gamma$ -rays in Active Galactic Nuclei [4, 3, 11] and X-ray binaries [1, 18, 10, 29]. The contribution of the synchrotron emission from the jet to the hard X-rays might also be significant [19].

However, the Comptonization spectra cannot provide, by themselves, information about the geometry and the

dynamics of the Comptonizing electrons, i.e., one can obtain similar energy spectra from rather different geometric configurations of the Comptonizing cloud [32]. In addition to the energy spectra, time variability information is needed [14]. Moreover, it has been observed [23] that the phase lags (not the time lags) between the signals in two different X-ray energy bands are approximately constant with Fourier frequency. This cannot be explained if Comptonization takes place in a hot, uniform, low-density plasma. A clever way to bring into terms thermal Comptonization and timing behavior was to consider a stratified spherical medium with density inversely proportional to radius [13, 15, 16, 14].

Recently, Reig et al. [27] proposed a jet model for the energy and time-lag spectra of black-hole X-ray sources in the low/hard state. The relativistic electrons in the jet upscatter a fraction of the soft photons emitted by the accretion disk and this produces the power-law energy spectrum. Power-law energy spectra with index in the range 1.5 - 2 are produced with reasonable values of the parameters describing the relativistic electrons in the jet. In addition, they showed for the first time that, by considering a jet with density inversely proportional to distance from the black hole, the nearly constant phase lags with Fourier frequency can be reproduced. For an alternate interpretation of time lags in black-hole candidates see Kotov et al. [17].

Here, we propose an extension of the model of Reig et al. [27], which in addition explains the increase of the amplitude of variability (quasiperiodic oscillations (QPO) and high frequency) with increasing photon en-

ergy. Our model makes the assumption that the jet is hotter near its center than at its periphery. Since it is generally believed that the photons that participate in the QPO and the high-frequency variability come from the inner part of the accretion disk, they are upscattered mainly in the hotter part of the jet, which is directly above the inner accretion disk. Thus, these photons are more efficiently upscattered (i.e., they gain more energy with fewer scatterings) than the rest of the photons from the accretion disk, which are upscattered mainly in the outer/cooler part of the jet.

## THE MODEL

### Characteristics of the jet

We consider the simplest extension of the model of [27] that we can think, which reproduces the energy spectrum, the time lags versus Fourier frequency that have been observed, and the increase of the high-frequency variability with photon energy. The characteristics of the assumed jet are the following:

i) We assume the speed of the relativistic electrons in the jet to be constant.

ii) We assume that there exists a uniform magnetic field along the axis of the jet (taken to be the  $z$  axis) and that the velocity of the electrons  $\vec{v}$  consists of two components: one parallel to the magnetic field  $\vec{v}_{\parallel}$  and one perpendicular to it  $\vec{v}_{\perp}$ . In other words, the electrons in the jet are spiraling along the magnetic field lines. This upscattering mechanism is reminiscent of thermal Comptonization because the photons sample electrons with all possible velocities [32].

iii) We take the electron-density profile in the jet to be of the form

$$n_e(z) = n_0 z_0 / z \quad (1)$$

where  $z$  is the vertical distance from the black hole and the parameters  $n_0$  and  $z_0$  are the electron density and height at the base of the jet respectively. If  $H$  is the height of the jet, then the Thomson optical depth along the axis of the jet is

$$\tau_{\parallel} = n_0 \sigma_T z_0 \ln(H/z_0), \quad (2)$$

where  $\sigma_T$  is the Thomson cross section.

iv) Let  $\pi r^2$  be the cross sectional area of the jet at height  $z$ . Then, from the continuity equation  $\dot{M} = \pi r^2 m_p n_e(z) v_{\parallel}$ , we obtain for the dependence of the radius  $r$  on height  $z$  that

$$r = (r_0^2 z / z_0)^{1/2}, \quad (3)$$

where  $r_0 = (\dot{M} / \pi m_p n_0 v_{\parallel})^{1/2}$  is the cross sectional radius of the jet at its base,  $\dot{M}$  is the mass ejection rate and

$m_p$  is the proton mass. Our jet is therefore focused, in agreement with observations [8]. The half Thomson optical depth of the jet at height  $z$  is

$$\tau_{\perp}(z) = n_0 \sigma_T r_0 (z_0/z)^{1/2}. \quad (4)$$

In order to simulate a jet which is hotter at its center than at its periphery, we assume that the perpendicular component of the electron velocity is  $v_{\perp}$  on the axis of the jet and it drops linearly and by a factor of 2 from the axis of the jet to its periphery.

## The Monte Carlo code

For our Monte Carlo code we follow Cashwell & Everett [5] and Pozdnyakov et al. [25]. A similar code was described in previous work by Reig et al. [28, 27]. The procedure is as follows:

Photons from a blackbody distribution of characteristic temperature  $T_{\text{bb}}$  are injected at the base of the jet with an upward isotropic distribution. As the photons travel through the medium, they experience Compton scatterings with the spiraling electrons. If the effective optical depth that they encounter is small (of order 1 or less), the majority of the input photons escape unscattered. If the effective optical depth is moderate, then the photons randomly walk through the medium prior to escape and on average gain energy from the circular motion (i.e.,  $\vec{v}_{\perp}$ ) of the electrons. Such Comptonization can occur everywhere in the jet.

If the defining parameters of a photon (position, direction, energy and weight) at each stage of its flight are computed, then we can determine the spectrum of the radiation emerging from the scattering medium and the time delay of each escaping photon. The optical depth to electron scattering, the frequency shift and the new direction of the photons after scattering are computed using the corresponding relativistic expressions. The extra time of flight of each photon outside the jet is taken into account in order to bring in step all the photons escaping in a given direction.

## PARAMETER VALUES

The high-energy X-ray spectra of black-hole candidates in the low/hard state are characterized by a power law with photon-number spectral index  $\Gamma$  in the range 1.5 - 2 and a high-energy cutoff  $E_{\text{cut}}$  in the range 150 - 300 keV (see e.g. Tanaka & Shibazaki [31]). In addition, the soft thermal component, so prominent in the high/soft state and interpreted as radiation from a cold accretion disk, never totally disappears in the low/hard state. There is evidence for a soft excess with blackbody temperatures

$kT_{\text{bb}} \sim 0.1 - 0.3$  keV [2, 36]. In particular, for Cyg X-1 these parameters are  $kT_{\text{bb}} = 0.13$  keV,  $\Gamma = 1.6$ ,  $E_{\text{cut}} = 160$  keV [7, 6]. Thus we have considered a blackbody function with  $kT_{\text{bb}} = 0.2$  keV as the input source of soft photons in all the calculations presented in this work. Our conclusions are unchanged for  $kT_{\text{bb}}$  in the range 0.1 - 0.3 keV.

Observed time lags of the order of a fraction of a second, if interpreted as light-travel times, require a height  $H$  of the jet at least of the order of  $10^{10}$  cm. In our calculations we have taken  $H = 2 \times 10^5 r_g$ , where  $r_g = (GM/R)^{1/2}$  is the gravitational radius of a black hole of mass  $M$  and horizon radius  $R$ . Thus, for a 10 solar-mass black hole  $H = 3 \times 10^{11}$  cm.

Both  $E_{\text{cut}}$  and  $\Gamma$  depend on the velocity of the electrons in the Comptonizing medium. In order to produce spectra similar to the ones observed, we restricted the values of  $v$  and  $v_{\perp}$  to the ranges  $0.7c - 0.9c$  and  $0.3c - 0.5c$  respectively. When another parameter in our calculations is varied, we take  $v = 0.85c$  and  $v_{\perp} = 0.4c$ .

Another parameter of our model that affects the slope of the resulting energy spectra is the width of the jet, since in a too narrow a jet too few photons are upscattered. The base of the jet was fixed at a distance of  $z_0 = 20r_g$  from the black hole, whereas  $r_0$  was varied in the range  $75r_g - 300r_g$ . When another parameter in our calculations is varied, we take  $r_0 = 200r_g$ .

In order to have enough scatterings to produce the desired power-law energy spectra, we have taken  $\tau_{\parallel}$  in the range 3 - 15, with fixed value  $\tau_{\parallel} = 10$  when another parameter is varied. Note that the effective optical depth that the emitted photons see is significantly less than this due to the high velocity of the electrons in the jet.

Finally, given the high values of  $v_{\parallel}$  invoked in our model, we expect an angular dependence of the power-law X-ray spectra. From observations of Galactic microquasars we know that the angle between the observational direction and the axis of the jet lies in the range  $70^{\circ} - 85^{\circ}$  [21]. When a parameter is varied in our model, we restrict ourselves to photons recorded in the range  $0.1 < \cos \theta < 0.3$  or  $84^{\circ} > \theta > 72^{\circ}$ , where  $\theta$  is the angle between the direction of motion of the jet and the line of sight.

A thorough study of the dependence of the energy and time-lag spectra as well as the high-frequency variability on the different parameters will be presented in a forthcoming paper (Giannios et al., in preparation).

## RESULTS AND DISCUSSION

In order to compute the energy spectra and the light curves we binned the energy of the escaping photons, their travel time and their direction cosine with respect

to the axis of the jet.

### Energy spectra

As demonstrated by Reig et al. [27], the computed spectra exhibit a soft, thermal-type component and a hard, power-law type component with a high-energy cut-off.

The photon-number spectral index  $\Gamma$  (of the hard power-law tail in the energy range 10 - 100 keV) lies in the interval  $\sim 1.5 - 2$ , for a wide range of the parameters. These values are similar to those observed in the low/hard state of black-hole candidates [31]. The thicker the medium the flatter the spectrum. The component  $v_{\perp}$  must be a significant fraction of the total speed of the electrons in order to have  $\Gamma$  in the range 1.5 - 2. The larger  $v_{\perp}$  the flatter the spectrum.

### Time lags

The time of flight of all escaping photons was recorded in 8192 time bins of duration 1/128 s each. This time was computed by adding up the path lengths traveled by each photon and dividing by the speed of light. Then we considered the light curves of two energy bands: 2 - 5 keV and 14 - 45 keV. Following Vaughan & Nowak (1997), we computed the phase lag and through it the time lag between the two energy bands as a function of Fourier frequency.

As demonstrated by Reig et al. [27], the time-lag spectrum is roughly represented by a power law  $\nu^{-\beta}$  with index  $\beta = 0.7$  in the frequency range 0.3 - 30 Hz, in excellent agreement with the results by Nowak et al. [24] for Cyg X-1.

### High-frequency variability

In order to demonstrate that it is possible in Comptonization models to have increasing variability with photon energy, we did the following: We first injected soft photons from the entire accretion disk. These photons sampled the entire jet, i.e., both its inner/hotter part and its outer/cooler part. Let  $F_1(E)$  be the output power-law spectrum above, say, 1 keV. Then we injected soft photons at the center of the base of the jet. These photons scattered mainly in the inner/hotter part of the jet and produced a power-law spectrum  $F_2(E)$ , which is flatter than  $F_1(E)$ . Thus, the ratio  $[F_2(E) - F_1(E)]/F_1(E)$  is an increasing function of photon energy. In other words, the soft input photons that participate in the QPO and the high-frequency variability exhibit an increasing variability

ity with photon energy when they are observed as power-law photons.

## CONCLUSION

We have shown that Compton upscattering of low-energy photons in a jet can explain not only the energy and time-lag spectra in black-hole X-ray sources in the low/hard state but also the increase of high-frequency variability with photon energy. For reasonable values of the model parameters we are able to reproduce the energy and time-lag spectra of Cyg X-1 in the low/hard state as well as the observed changes of the power-density spectrum with photon energy.

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